AFRL-RH-WP-TP-2014-0028

Test Equipment and Method to Characterize a SWIR Digital Imaging System

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June 2014

INTERIM TECHNICAL PAPER

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REPORT DOCUMENTATION PAGE

1. REPORT DATE *(DD-MM-YY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
13-06-14	Interim (Technical Paper)	16 Jun 2013 – 7 May 2014

4. TITLE AND SUBTITLE

Test Equipment and Method to Characterize a SWIR Digital Imaging System

5a. CONTRACT NUMBER
FA8650-08-D-6801-0050

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
Multiple

6. AUTHOR(S)

John Green and Tim Robinson

5d. PROJECT NUMBER
5239

5e. TASK NUMBER
11

5f. WORK UNIT NUMBER
H0CK (Historic: 53291102)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)z

Esterline Control and Communication Systems – Korry Electronics Co.
11910 Beverly Park Road
Everett WA 98204

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Material Command
Air Force Research Laboratory
711 Human Performance Wing, Human Effectiveness Directorate
Warfighter Interface Division, Battlespace Visualization Branch
Wright-Patterson Air Force Base OH 45433-7022

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
USAF AFMC 711 HPW/RHCV

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-RH-WP-TP-2014-0028

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution A: Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES 88ABW Cleared 03/20/2014; 88ABW-2014-1130. Report contains color.

14. ABSTRACT This paper describes test equipment and methods used to characterize short-wave infrared (SWIR) digital imaging systems. The test equipment was originally developed under the Air Force Research Laboratory (AFRL) contract Advanced Night Vision Imaging System – Cockpit Integration (ANVS-CI) and refined under CRADA NUMBER 13-168-RH-01CRD between 711 HPW/RHC and Esterline-Korry Electronics. The test equipment measures relative spectral responsivity, noise equivalent irradiance, dynamic range, linearity, dark noise, image uniformity, and captures image artifacts.

15. SUBJECT TERMS Visualization of Complex 4D Data, V4D, Alternative Night/day Imaging Technologies, ANIT, Shortwave Infrared, Imaging System, Focal Plane Array, Test Methods, Irradiance, Spectral Responsivity

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Darrel G. Hopper
Unclassified	Unclassified	Unclassified	SAR	19	**19b. TELEPHONE NUMBER** *(Include Area Code)*

Technical Paper (TP)

Test Equipment and Method to Characterize a SWIR Digital Imaging System

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Short Title: SWIR Imager Characterization

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INTRODUCTION

Shortwave Infrared (SWIR) Focal Plane Array (FPA) Imaging Systems have emerged as viable and important technology for military and commercial applications. This is largely based on improvements impacting sensitivity, resolution, frame rate, size, power consumption, and unit cost. Air Force Research Laboratory (AFRL) has particular interest in helmet mounted FPA imaging systems that offer a significant advantage to the US war fighter by providing enhanced vision in the SWIR band.

There are several manufacturers of uncooled SWIR cameras. Given the increasing number of manufactures and various camera options available, it is beneficial to characterize the imaging systems using common test and analysis methods from an end-user's point of view. By adopting common methods, various imaging systems manufactured by different OEMs can be compared.

This paper describes test equipment and procedures developed for AFRL to characterize the performance of digital SWIR imaging systems. The equipment has been used to measure Relative Spectral Responsivity, Noise Equivalent Irradiance (NEI), Dynamic Range, System Linearity, Pixel Characteristics, Dark Noise, and Image Uniformity for a fully assembled SWIR camera. [1] It has also been used to capture Image Artifacts. The system level requirements for the test equipment are described in the next section.

SYSTEM LEVEL REQUIREMENTS

Analog imaging systems based on Gallium Arsenide (GaAs) detectors are sensitive in the visible and near infrared (NIR) bands, and used only at night. They produce images from electrons emitted by the GaAs impinging on a phosphor screen. These analog systems are tested with low irradiance light sources, and often evaluated through subjective means. [2]

SWIR digital imaging sensors overcome many limitations present in traditional analog technologies. Key areas of advancement include Indium Gallium Arsenide (InGaAs) sensor technology with a wide dynamic range useful for day and night applications, a spectral responsivity that extends to at least 1.7 μm, and a digital data stream from the sensor. Furthermore, the spectral responsivity is tunable by the manufacturer; the detection range may be extended into the visible band by reducing the sensor substrate thickness, and extended further in the SWIR band by manipulating the sensor material stoichiometry. Test equipment designed to characterize digital imaging cameras must have the flexibility to capture these benefits.

The test system requirements must also take into the dynamic range associated with the target avionics application. As already stated, traditional night vision goggles (NVGs) are used for night operations only. NVGs are generally characterized using a 2856K incandescent lamp set to 0.1 fL to represent night NIR irradiance levels. Since the SWIR imaging system is useful for both day and night operations, the test system should be designed with a wide irradiance dynamic range to simulate both day and night levels.

Figure 2 shows the spectral irradiance for high intensity sunlight and low intensity night glow from 0.5 to 1.8 μm. [3], [4] Each data set contains sharp spectral features associated with either atmospheric absorption or emission events. [5] The spectral gap near 1400 nm is caused by a large atmospheric humidity absorption band. [6] The irradiance difference between day and night is approximately 11 decades in the visible band and 8 decades in the SWIR band. A camera useful for both day and night application must have a saturation limit that allows for detection at the irradiance levels produced during the day, and have a noise floor less than the minimum night time irradiance levels. The figure also shows that a 3000 K blackbody source set to appropriate irradiance levels may approximate the SWIR day spectrum while a 1300 K blackbody source may approximate SWIR night glow.
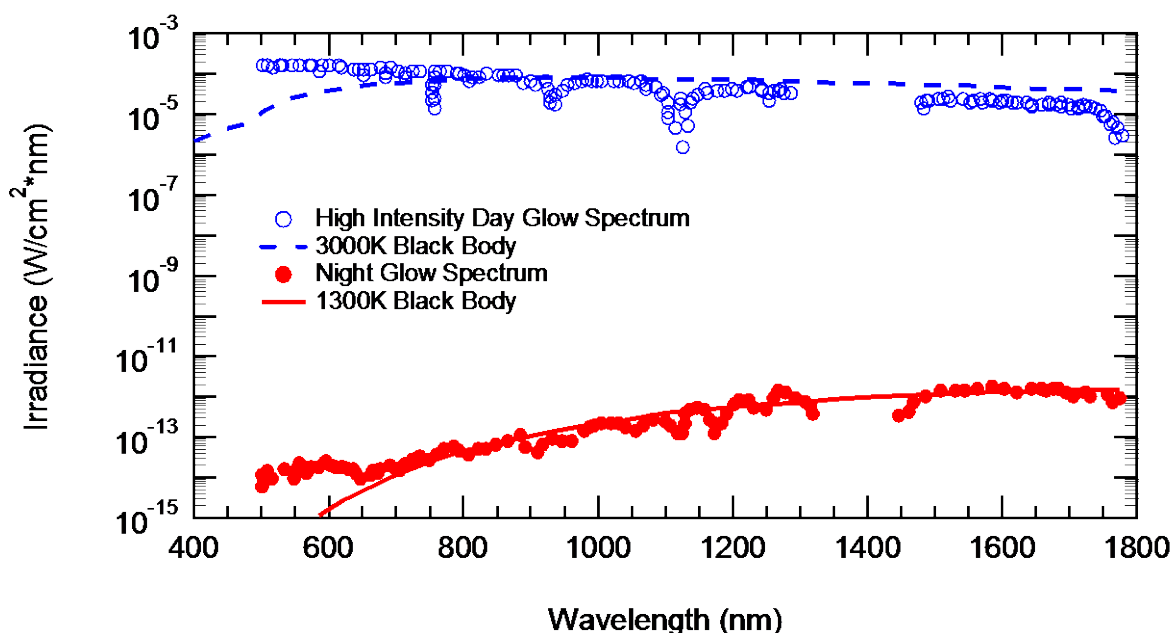

Figure 1: Day and Night Glow Spectra (Terrestrial Data); Black Body Spectra approximating the Day and Night Glow

Figure 1 estimates the dynamic range and minimum irradiance levels available to the camera when used in an open-air environment. However, our target application has two additional factors that must be accounted for. The pilot views the world through a cockpit transparency which can attenuate approximately 10% of the SWIR band. In addition and like NVG specifications, system limitations are based on night irradiance reflections from low reflective objects. For SWIR imaging systems, a 20% reflectance throughout the SWIR band is assumed. [7] Taking these factors into account, the minimum night glow irradiance available to a pilot is approximately 2 decades less than shown in figure 1. Therefore, the test bench must have a dynamic range in the SWIR band no less than 10 decades and produce a minimum irradiance level at 1550 nm no greater than 2×10^{-14} W/cm^2.

The image analysis is performed over the entire focal plane array. The irradiance flux incident across the entire FPA must be well characterized at the various test distances. Any deviation from uniformity must be minimized and quantified to correct the baseline of the image data. For this system, the target flux area is 50 x 38 mm with a uniformity > 98% at test positions 11.5 and 22 inches away from the irradiance source.

Table 1 summarizes the primary target requirements for the test equipment. The system calibrated with Germanium sensors has a spectral range appropriate for a non-extended InGaAs imaging system. However, the test equipment is designed and can be calibrated for extended InGaAs imaging systems with a range from 600 to 2500 nm.

Table 1: Test Equipment Optical Requirements

Property	Target Requirement
Dynamic Range at 1550 nm	10 Decades
Minimum Irradiance at 1550 nm	2×10^{-14} W/cm^2
Flux Uniformity at 22 inches over a 50 x 38 mm area	>98%
Spectral Range (with Si and Ge Calibration Sensors)	600 – 1800 nm
System Monochromator Range	600 – 2500 nm

EQUIPMENT DESCRIPTION

The test system is composed of three distinct elements. The first element controls and acquires data from the device under test (DUT). It also controls and acquires data from test equipment components such as a monochromator, source lamps, variable apertures (for light level control), picoammeters, and position/stage controllers. The second element is a data processing program that enables the user to manipulate and evaluate images captured under various conditions. The third element consists of various commercially available or open-source data analysis software packages for data evaluation and reporting on the imaging systems properties such as spectral range, NEI, dynamic range, uniformity, etc. The relationship among these three elements is in figure 2. The three fore mentioned elements are listed in the figure as **System Control and Data Acquisition**, **Data Processing**, and **Data Analysis**.

The system hardware uses interface converters to connect the various test equipment components to an Ethernet backbone. This design minimizes the types of interface connections, minimizes obsolescence issues around computers and computer interface components, and enables the creation of a single software protocol for test equipment communication. As such, the computer can be virtualized and the user can operate the equipment and access the data from a remote location.
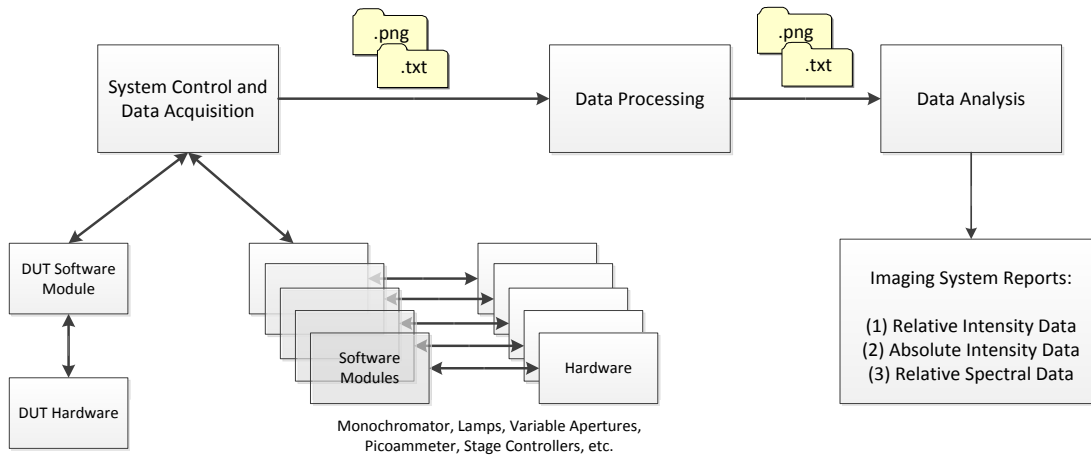
Figure 2: Test Equipment Architecture

1.1 System Control and Data Acquisition

The System Control and Data Acquisition portion of the Test System consists of hardware and software elements. The software element is a LabVIEW program that contains a sequencing module and software drivers for each of the hardware components. Test scripts are created by dragging and dropping LabVIEW controls from the software driver to a sequence list. The data is collected for post processing as the software driver read functions are executed. Test script loops are created to perform experiments, such as stepping the monochromator through wavelengths while collecting images and reference current values.

Figure 3 shows the user interface for the System Control and Data Acquisition program. The left column lists the available software drivers; highlighted is a SWIR camera driver. The columns to the right provide actionable LabVIEW controls, including (1) selection of software drive (instrument), (2) selection of control name, (3) the value of associated with the control, and (4) the type of action to undertake. The right section of the figure shows the user interface for the selected driver. The controls enable the user to take an image (Snap), stream images (Grab), and save images with selected meta-data. A subset of the camera controls are available and can be modified by the sequence module.

Figures 4 and 5 show the schematic and the physical model for the System Control and Data Acquisition hardware. The system has three light sources to generate the wide dynamic range specified in the previous section. 250W and 20W Tungsten filament lamps with a nominal color temperature of 3000K are used to simulate the day irradiance spectrum. A 15W glow bar with a nominal color temperature of 1300K is used to simulate the night irradiance spectrum. The 20 W and 15 W sources are located in satellite spheres attached to the primary sphere. The flux intensity from each lamp is controlled by a programmable variable aperture thereby maintaining constant color temperature. The lamps flood a 12" integrating sphere through these apertures. The integrating sphere is gold coated for maximum SWIR band efficiency. The sphere has a four inch exit port; this port provides the source of irradiance incident on the DUT.
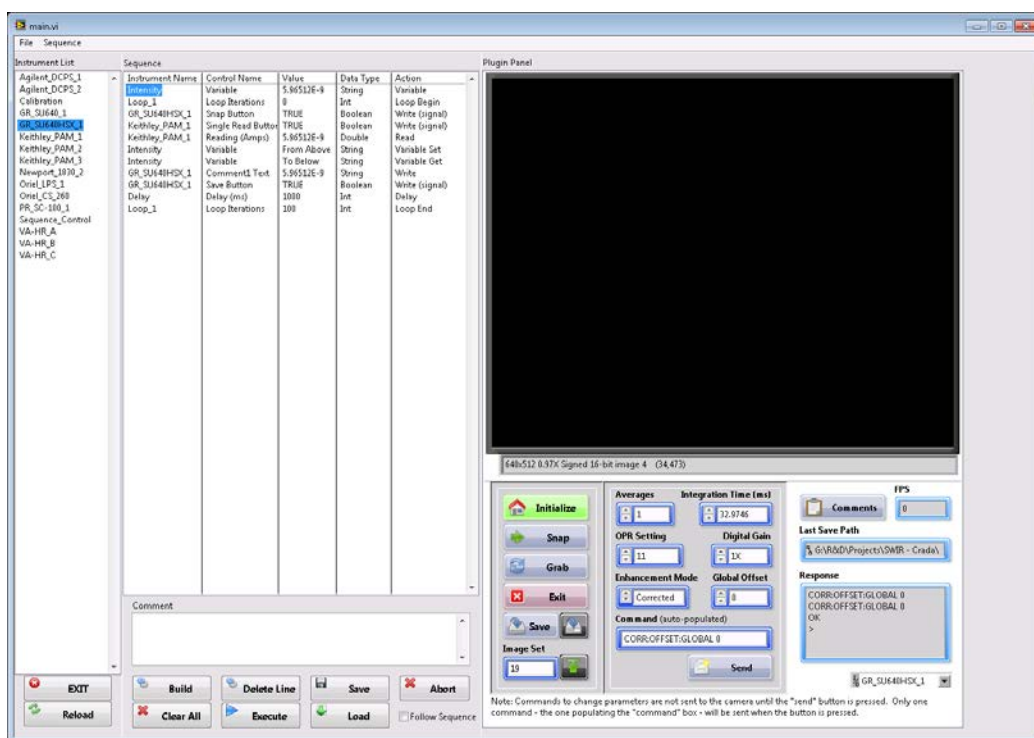

Figure 3: Graphic User Interface for the System Control and Data Acquisition Element

A separate 250W lamp is used with a monochromator to provide a spectral source from the far-visible through the SWIR band. A filter wheel containing order sorting filters is attached to the exit port of the monochromator. Monochromatic light enters the sphere through this filter wheel. This part of the test system is used to determine the spectral responsivity of the DUT.

A primary set of photodiodes can be located at the DUT position (shown in figure 4 as 22 inches from the exit port). These primary photodiodes are used for calibration, verification, and irradiance uniformity tests. Silicon and Germanium secondary photodiodes are each mounted on the sphere. The secondary photodiodes are used to monitor the sphere's intensity during a DUT measurement sequence.

The DUT is mounted on a bracket attached to a motor controlled positioning stage. The nominal test distance between the DUT's FPA and the exit port is 22 inches; however the DUT may be moved closer to the exit port if the irradiance flux intensity is too low. There are black baffles extending from the exit port to minimize the impact of stray light from the outside environment. The entire test system is mounted on an optical bench, which is located within black curtains, and this curtained off area is in an optical darkroom.
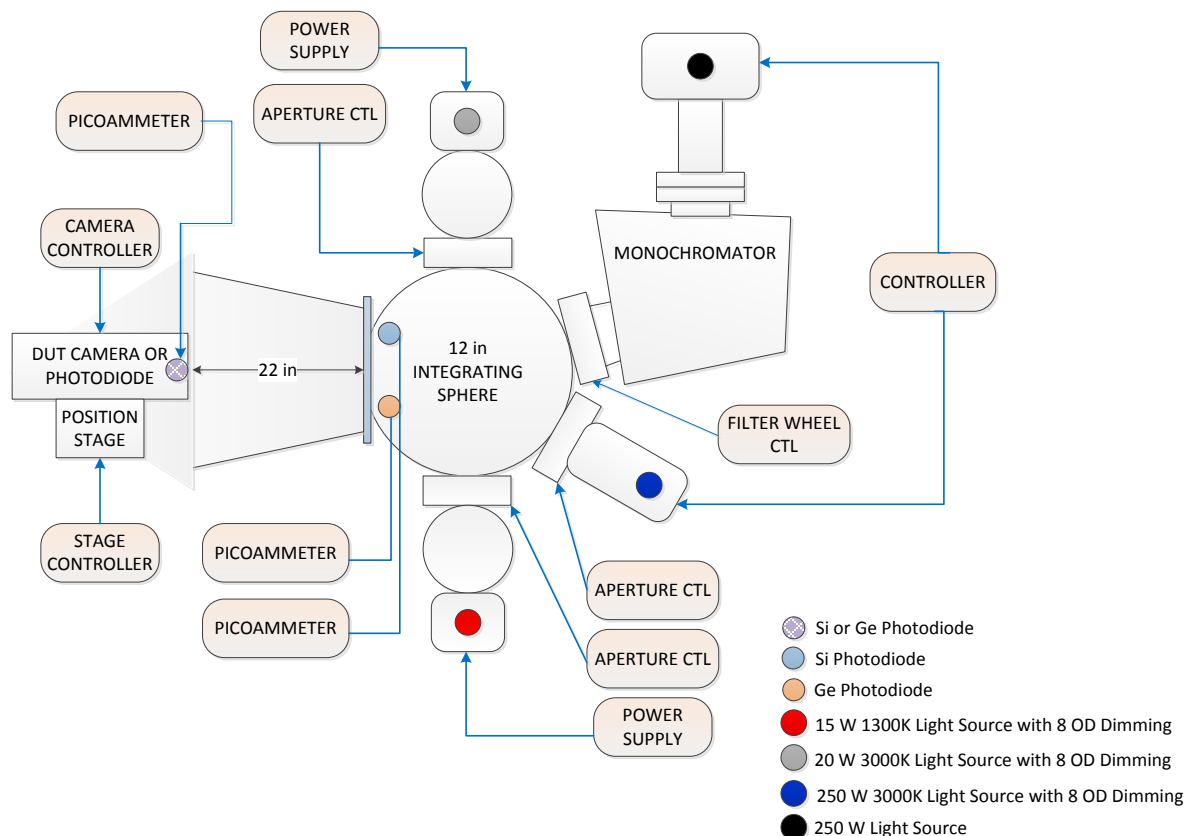

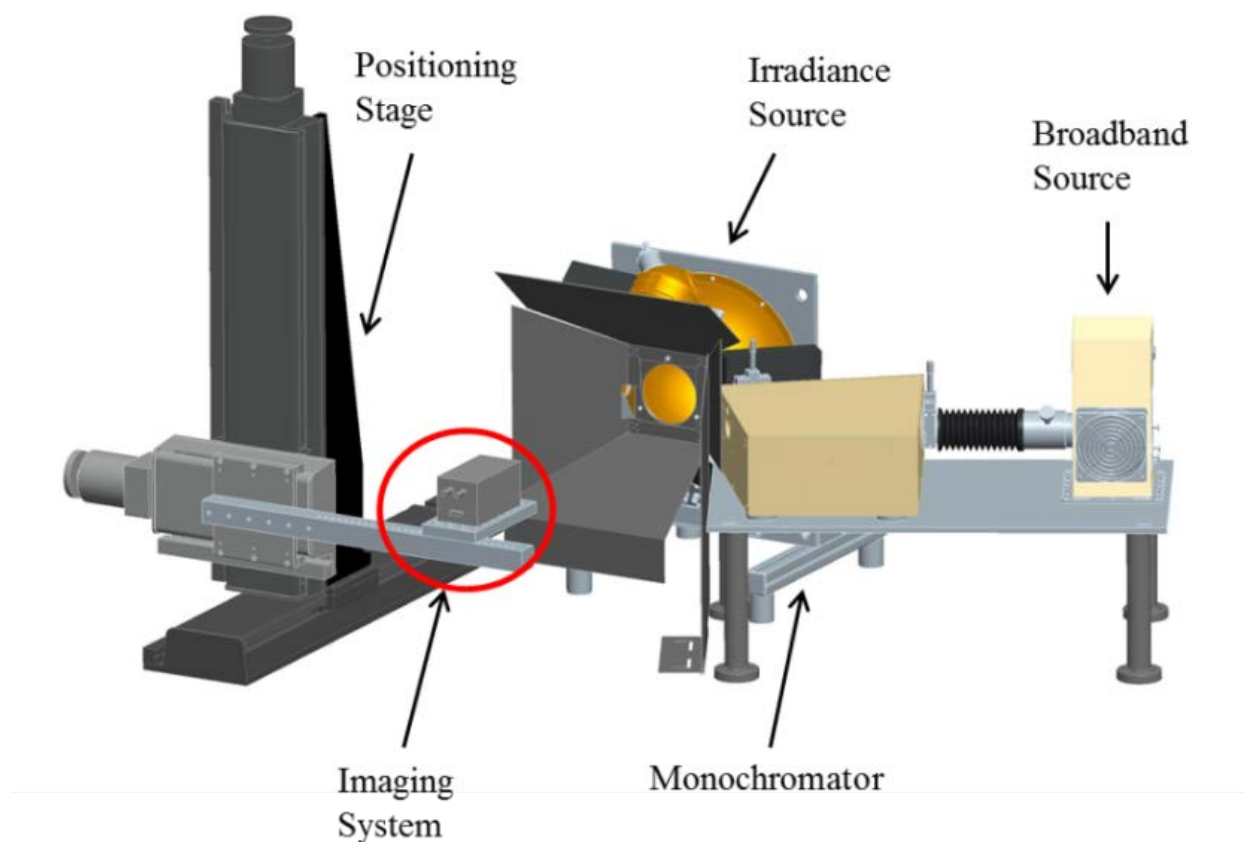**Figure 4: System Control and Data Acquisition Hardware Schematic**

Figure 5: System Control and Data Acquisition Physical Model

1.2 Data Processing

The Data Processing program receives digital imaging files with embedded meta-data and supplementary data files from the System Control and Data Acquisition element. The digital imaging files are saved in a Portable Network Graphics (.png) file format. A screen shot of the Data Processing user interface is in Figure 6. The left column contains selection icons for creating different types of new images, performing mathematical operations on the select area-of-interest (AOI) within images, and opening and saving images. The adjacent column to the right is the list of working images. An image or groups of images can be selected and dragged-and-dropped on controls such as Set1 and Set2. If a single image is selected then the image and associated meta-data is in the right hand portion of the user interface.

Using one of the four results buttons, the program generates numerical results from the AOI of selected images found in Set1. Results include the digital number mean, standard deviation, histogram, and profiles. A list of pixel values from the same location over multiple images can also be obtained for further processing.

The Data Processing program also performs two special functions important to the image analysis. These functions are used to determine "good" pixels and to create source uniformity correction images. Four images obtained with different flux values are used to determine "good" pixels based on the following criteria:

(1)   Does the pixel exhibit a constant non-zero output for all flux values?
(2)   Does the pixel exhibit zero output for all flux values?
(3)   Does the linearity of a pixel exceed the threshold correlation coefficient value?
(4)   Does the pixel exhibit zero output at low flux levels, but is otherwise responsive?
(5)   Does the pixel have abnormal dark field output?
(6)   Does the pixel have abnormal low dark field output?

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Good pixel maps are established in this data processing step; only the value of pixels deemed "good" are used in the analysis of images.

The second special function is the creation of source uniformity corrections maps. A text data file containing the flux measurements sampled at the DUT plane are loaded into the program. The flux measurements are interpolated to create an image having corrections factors for each pixel normalized to the center value.

These maps, coupled with an irradiance responsivity factor associated with the irradiance source, provide the baseline to evaluate specific camera performance parameters (NEI, spectral responsivity, dynamic range, pixel linearity, etc.).
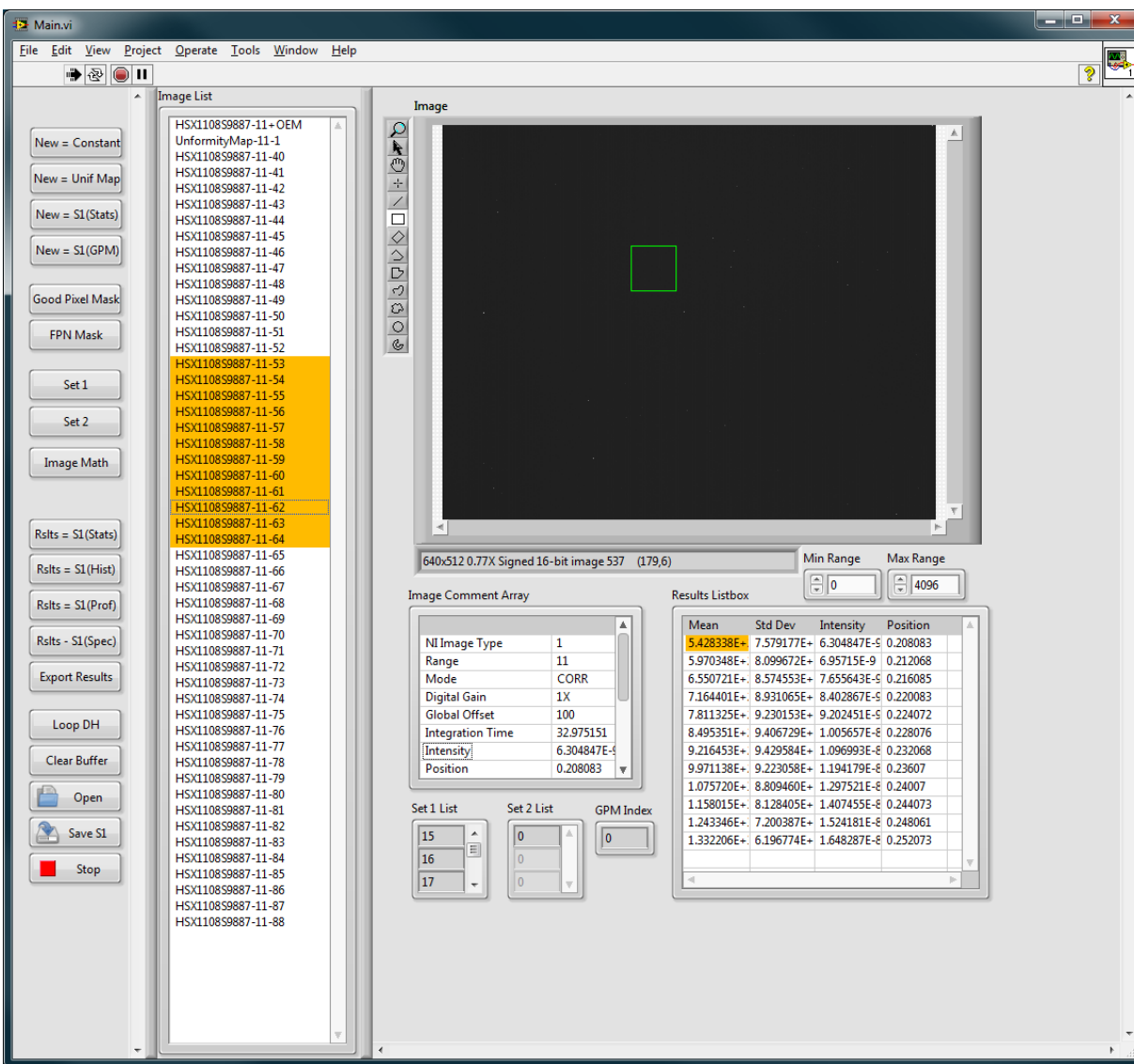

Figure 6: Graphic User Interface for the Data Processing Element

1.3 Data Analysis

Figure 7 shows the data flow map for the entire test system. The Data Analysis programs that generate the final report (shown at bottom and lower right section of the figure) receive raw digital files, processed digital files, and meta-data from the Data Processing program. The Data Analysis programs analyze this information to provide the DUT performance final report. The final report consists three major categories; (1) relative spectral performance (spectral responsivity), (2) relative intensity performance (dynamic range, FPA image uniformity, and pixel linearity), and (3) absolute intensity performance (sensitivity or NEI). As shown in the figure, these categories are evaluated using previously obtained good pixel maps, image uniformity maps, and meta-data relevant to the specific analysis.
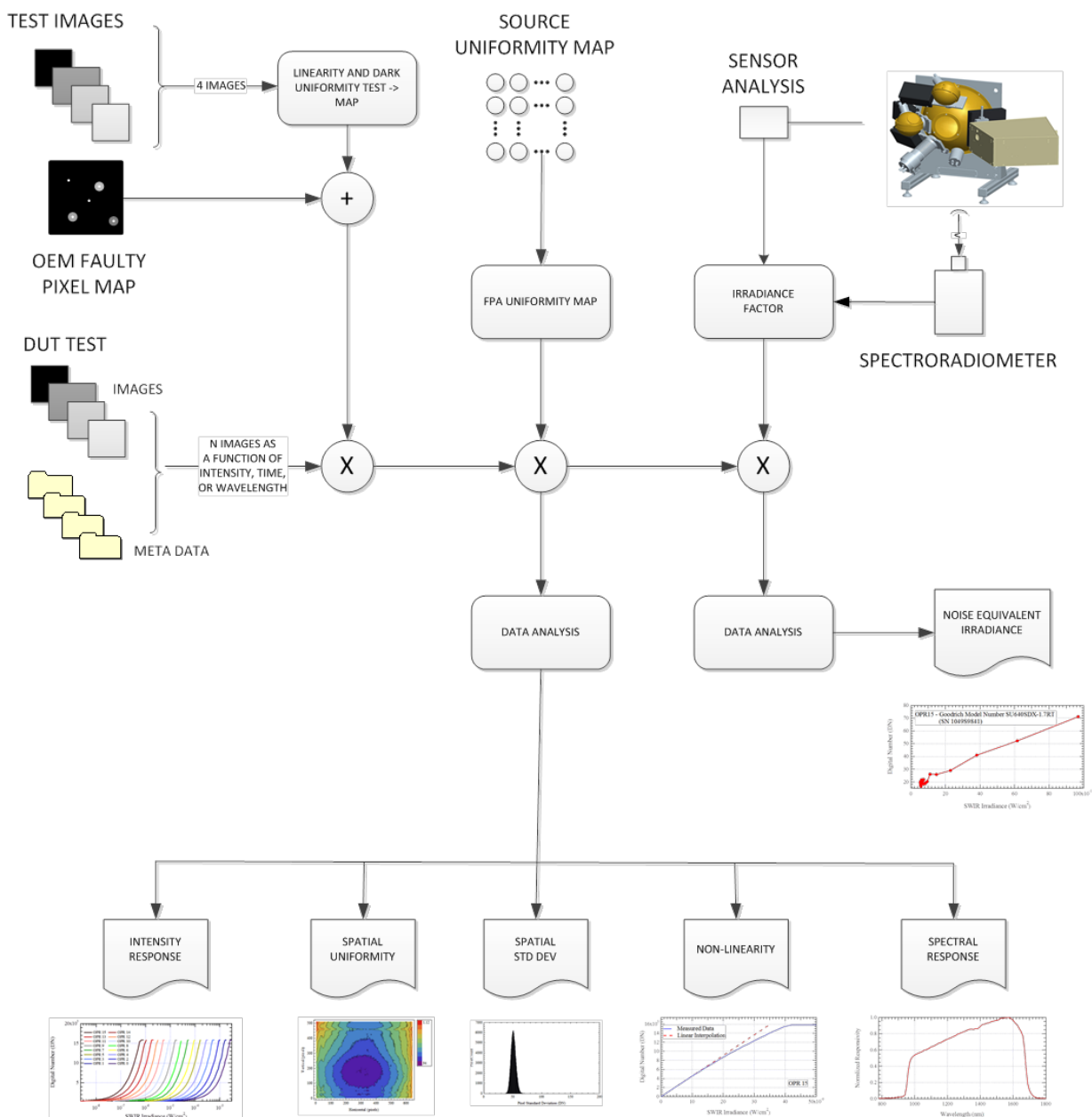

Figure 7: Data Flow Map through the Test System

SELECT TEST EQUIPMENT CALIBRATION AND VERIFICATION TESTS

Several components within the System Control and Data Acquisition hardware require calibration and/or verification. These components include the spectral irradiance of each lamp, responsivity of system sensors, dynamic range of the apertures, flux uniformity for the irradiance source, distance and alignment of the positioning stage, optical alignment, wavelength calibration, and bandpass calibration of the monochromator. The calibration and verification process for the system spectral irradiance, dynamic range, and the irradiance source spatial flux uniformity are described in this section.

1.4 System Spectral Irradiance

The test system elements that provide data used for irradiance analysis (15W, 20W and 250W lamp and the 12" integrating sphere) was calibrated by a third party and verified within the host optics laboratory. The third party initially calibrated a scanning, dispersive spectroradiometer using a U.S National Institute of Standards and Technology (NIST) traceable standard 1000W FEL type lamp and a NIST traceable diffuse reflectance standard. The calibrated spectroradiometer probe was then positioned 22 inches away from the exit port, each test system lamp activated, and the irradiance spectrum for each lamp collected.

The calibration was verified in the host optics laboratory using a calibrated Instrument Spectroradiometer System (ISS) 320. The ISS 320 irradiance probe was position 22 inches away from the exit port, the test lamps were activated, and the spectrum of the irradiance source collected. The calibrated spectrum is then compared to the verified spectrum. Figure 8 shows the comparison when using the glow bar lamp driven at a fixed current (2.369 A). As indicated in the graph, the calibrated and verified spectra within the SWIR band are reasonably aligned.
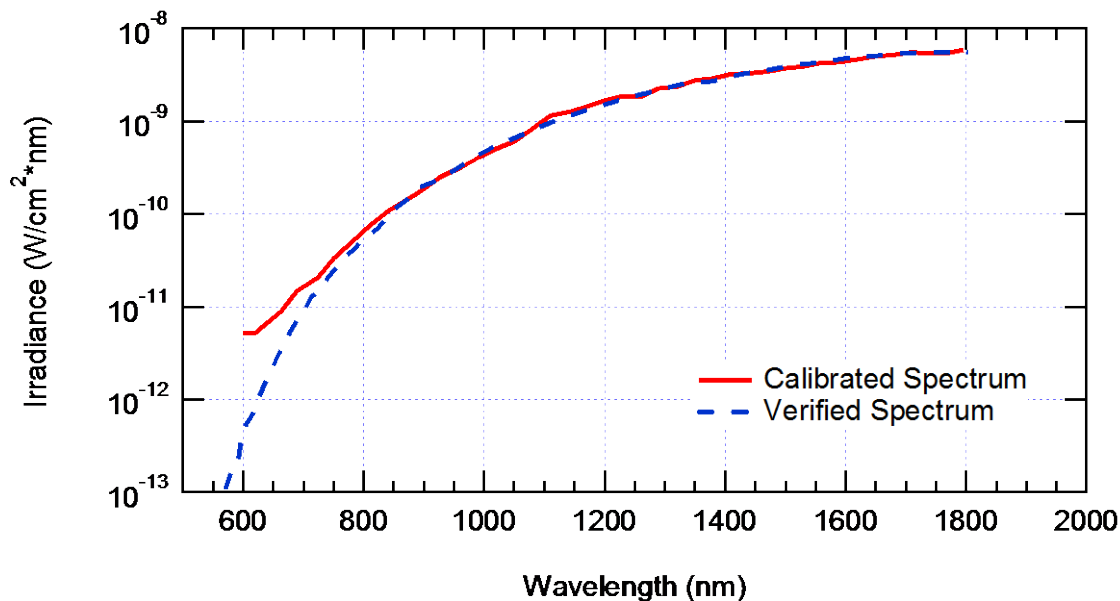

Figure 8: Glow Bar Lamp Calibrated and Verification Spectral Data

1.5 Absolute Spectral Irradiance

The absolute spectral irradiance was measured at 1550 nm and bench marked to the current from the silicon sensor located on the sphere. The irradiance responsivity, Rn, is the ratio of the silicon detector current and the absolute spectral irradiance at 1550 nm. The absolute spectral irradiance at different flux levels can be determined by scaling according to the relative silicon detector currents, in accordance with equation 1:

$$E_e(i_{Mon}, \lambda_{Cal}, n)[W/cm^2 nm] = \frac{i_{Mon}[A]}{R_n(i_{Cal}, \lambda_{Cal})[\,A/W/cm^2 nm]}$$

(1)

Where:

$R_n(i_{Cal}, \lambda_{Cal})$ = Irradiance responsivity factor at wavelength λ, lamp calibration current i, and of source n.

i_{Mon} = Measured current from the sphere mounted detector.

Table 2 lists the measure current value for the silicon sensor when the glow bar is illuminated and the aperture is fully open. The table also provides both the calculated responsivity factor (R_n) and the measured spectral irradiance at 1550 nm.

Table 2: Sensor Current, Responsivity, and Spectral Irradiance for the Glow Bar Lamp

Property	Value
Current (A) - Measured	7.746E-07
Responsivity at 1550 nm (A/W/cm^2*nm) - Calculated	1.870E+02
Spectral Irradiance at 1550 nm (W/cm^2*nm) - Measured	4.14E-09

1.6 System Dynamic Range

The dynamic range was designed to evaluate camera response from full sunlight to night glow in the shortwave infrared band. Each of the three lamps has a computer controlled high-resolution variable aperture that provides an irradiance flux over five orders of dynamic range. The system's minimum flux output is limited by light leakage through the fully closed aperture.

The dynamic range was verified using a Silicon detector calibrated with the system's spectral responsivity factor. The data was then correlated to irradiance at 1550 nm using the procedure described in section 4.2. The dynamic range was measured with the detector positioned at the DUT location, and the detector current as a function of aperture setting was recorded. The system's dynamic range is in figure 9.
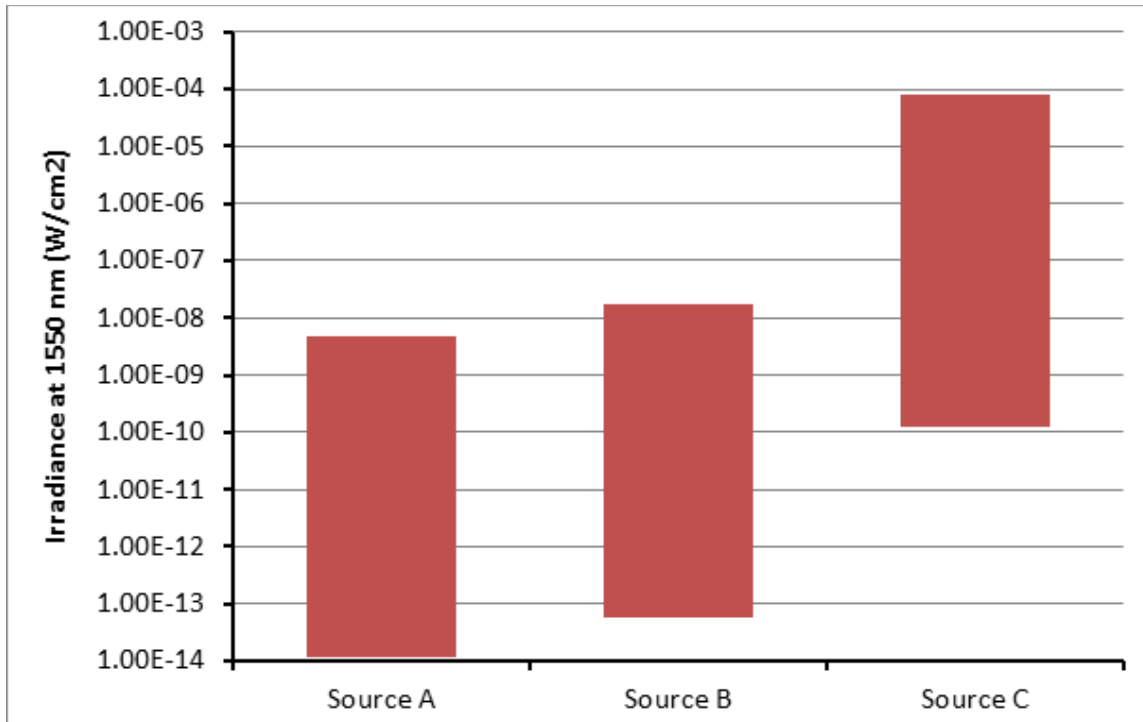
Figure 9: The Dynamic Range for the entire Test System. Source A is the Glow Bar Lamp; Source B is the 20 W Incandescent Lamp; Source C is the 250 W Incandescent Lamp.

1.7 System Spatial Flux Uniformity

The irradiance flux uniformity was measured with a Silicon detector having a 2.54 mm aperture, positioned at 11.5 and 22 inches away from the exit port. The detector was moved stepwise over a 2 x 1.8 inch area in increments of 0.1 inches. Figure 10 shows the flux uniformity of the system illuminated with the 15 W 1300K glow bar lamp measured at 22 inches from the exit port. The blue rectangle in the center of the plot represents the active area for the SWIR camera FPA (16 x 12.8 mm).
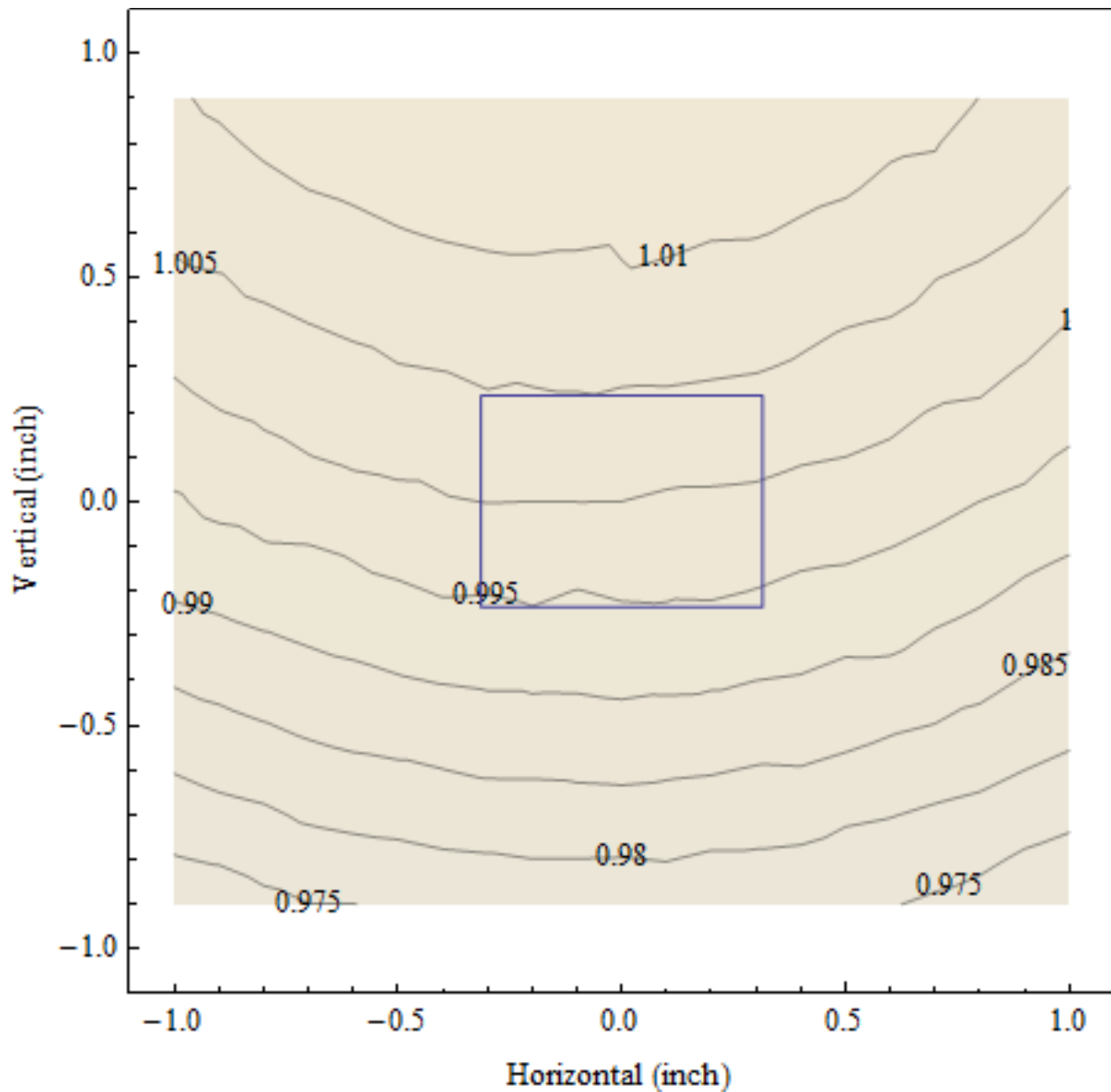
Figure 10: Flux Uniformity at 22 inches from the Itegrating Sphere Exit Port

The irradiance flux increases slightly along both the vertical and horizontal axes. The central region-of-interest shows a deviation of ±0.5% and ±0.1% along the vertical and horizontal axes respectively. An inverse deviation map generated from this data may be applied to the FPA output to correct for the non-uniformity of the incident flux.

SELECT CAMERA TEST RESULTS

This section describes select test results for a digital SWIR imaging system analyzed using the equipment and procedures described in the previous sections. Specifically, this section describes Image Uniformity and Spectral Responsivity. Other properties such as NEI, Good Pixel Maps, Dynamic Range, Pixel Linearity, and Dark Noise will be the subject of a future paper.

1.8 Image Uniformity

Spatial uniformity is a measurement of the focal plane array response to a uniform flux. System verification measurements show the uniformity of the incident flux is better than 0.5% at 22 inches from the exit port (see section 4.4). Spatial uniformity is measured by capturing 100 images at an approximate frame rate of one image per second. These images are obtained at four intensity levels, one of which is a dark field. From these images, the digital number mean and standard deviation are calculated for each pixel. The images are processed using only "good" pixels maps established prior to the image uniformity analysis.

Figure 11 shows the mean and standard deviation uniformity maps of the focal plane array for high flux irradiance. The mean image is normalized to the average DN value; the contour line with the value "1.0" represents the average DN value. The camera digital output ranges from +14 to -6% of this average. A digital depression is evident slightly below the middle region. The structure is tilted with an offset concaved surface and high peaks at the image field corners.
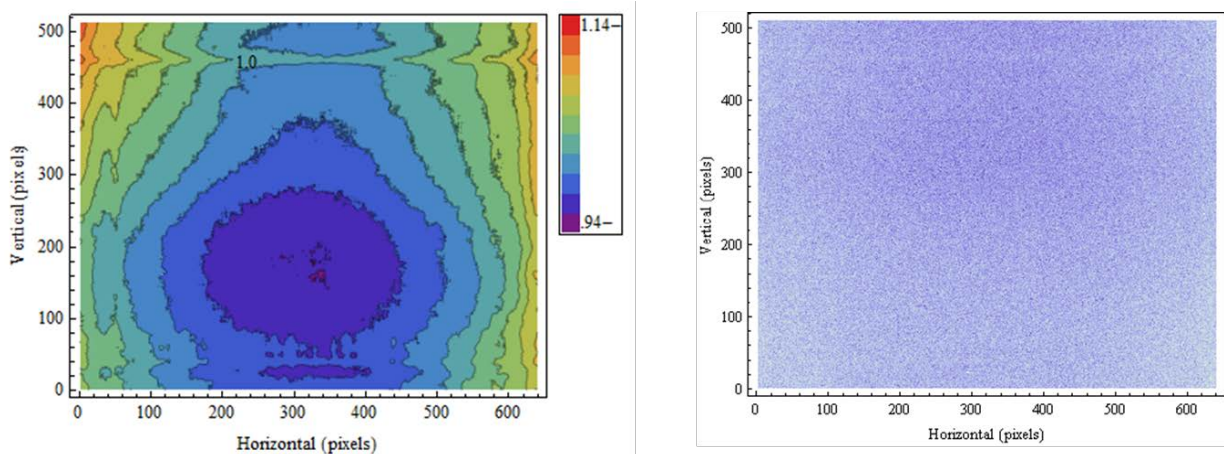

Figure 11: The Mean (left) and the Standard Deviation (right) Uniformity Maps for an FPA Illuminated with High Flux Irradiamce, positioned 22 inches away from the Exit Port, with the Camera set to uncorrected mode (Gain = 1X, Global Offset = 0).

The standard deviation uniformity map is predominately stochastic with an average value of approximately 50 DN. However, close inspection of the map reveals a structured frame of pixels near the perimeter of the FPA active area, most evident along the left and top sides. This structure is detectable with low to high irradiance flux levels and is associated with the camera.

1.9 Spectral Responsivity

The spectral responsivity of the imaging system is a measurement of the camera's sensitivity as a function of wavelength is determined by measuring the camera digital output relative to a Germanium monitor detector mounted on the central integrating sphere. The camera is then replaced by a calibrated Germanium detector, and a second measurement is taken of the calibrated (or reference) Germanium detector and the Germanium monitor detector.

Once measurements are obtained, the spectral responsivity is determined with equations (2) through (4). The first term of equation (3) is the ratio of the camera ROI mean to the monitor detector current. The second term is the

ratio of the monitor detector current to calibration detector current. The last term is the responsivity of the calibration detector. A responsivity curve is normalized to the maximum value in equation (4).

$$Camera(\lambda) = \frac{\sum_{i=0}^{n}\big(ROI(FPA(\lambda)_i)\big)}{n} \qquad (2)$$

$$\Re(\lambda)[DN/W] = \left(\frac{Camera(\lambda)[DN]}{MonDetCur(\lambda)[A]}\right)\left(\frac{MonDetCur(\lambda)[A]}{CalDetCur(\lambda)[A]}\right) \cdot CalDetResp(\lambda)[A/W] \qquad (3)$$

$$\Re(\lambda)_{Normalized} = \frac{\Re(\lambda)}{\|\Re(\lambda)\|_{Max}} \qquad (4)$$

Where:

$MonDetCur$ = the current measurement from the Germanium detector mounted on the sphere.

$CalDetCur$ = the current measurement from the Germanium detector mounted at the DUT location.

$CalDetResp$ = the responsivity of the Germanium calibration detector.

Figure 12 shows the measured normalized responsivity of the DUT. The spectral form is representative of previously published InGaAs spectral responsivity. [8]
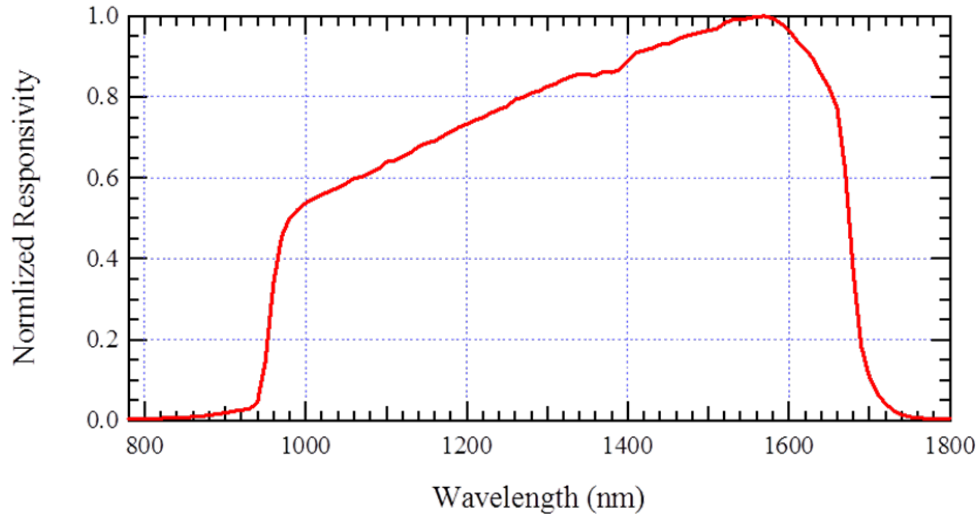

Figure 12: Spectral Responsivity of the SWIR Camera Under Test

CONCLUSION

The Department of Defense is interested in helmet mounted digital imaging systems for flight applications. It is envisioned these systems will augment, or in some cases, replace helmet mounted analog night vision goggles currently used by most flying US war fighters. It is generally recognized that there needs to be a way to compare various digital systems produced by different OEMs. Test equipment and methods have been developed to analyze the performance of fully assembled devices. Results of tests conducted with this system should provide the means to compare different imaging systems.

The test system is designed to produce a uniform irradiance flux that simulates sunlight and night glow spectral properties and intensities within the SWIR band. Digital information from the fully assembled camera resulting from exposure to the flux is used to determine FPA image uniformity, Noise Equivalent Irradiance (NEI), Dynamic Range, System Linearity, Pixel Characteristics, Dark Noise, and Image Artifacts. The test system is also equipped with a monochromator to obtain Relative Spectral Responsivity.

A subset of calibration and verification procedures used to confirm the accuracy of the test equipment has been described. The spectral output was verified by measuring the spectral power distribution of all lamps associated with the test system using an independent spectroradiometer. The absolute irradiance flux was established through a combination of calibration data provided by a third source and verification experiments. The flux uniformity of the system is 99.5% at the DUT position of 22 inches away from the exit port. The dynamic range of the test system was verified to be approximately 10 orders of magnitude and the minimum irradiance level verified at a value less than the system requirement ($2.0E-14$ W/cm^2). These results demonstrate that the test equipment meets the system level requirements necessary to characterize high performance digital imaging systems intended to be used in both day and night applications..

ACKNOWLEDGEMENT

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